BiTouch and BiPad: Designing Bimanual Interaction for Hand-held Tablets

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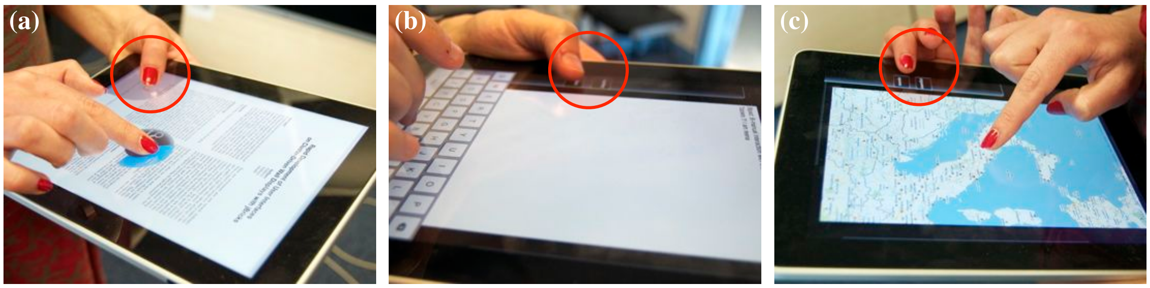

Figure 1. Bimanual interaction with BiPad: a) navigating a PDF, b) shifting to uppercase, c) zooming on a map. The non-dominant support hand can tap, make gestures or perform chords, thus modifying interaction by the dominant hand.

ABSTRACT
Despite the demonstrated benefits of bimanual interaction, most tablets use just one hand for interaction, to free the other for support. In a preliminary study, we identified five holds that permit simultaneous support and interaction, and noted that users frequently change position to combat fatigue. We then designed the BiTouch design space, which introduces a support function in the kinematic chain model for interacting with hand-held tablets, and developed BiPad, a toolkit for creating bimanual tablet interaction with the thumb or the fingers of the supporting hand. We ran a controlled experiment to explore how tablet orientation and hand position affect three novel techniques: bimanual taps, gestures and chords. Bimanual taps outperformed our one-handed control condition in both landscape and portrait orientations; bimanual chords and gestures in portrait mode only; and thumbs outperformed fingers, but were more tiring and less stable. Together, BiTouch and BiPad offer new opportunities for designing bimanual interaction on hand-held tablets.

Author Keywords
Bimanual Interaction; Hand-held tablets; Multi-touch tablets; BiTouch design space; BiPad.

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces—*Interaction styles; Input devices and strategies*

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INTRODUCTION
Multi-touch tablets have become increasingly popular over the past few years, combining relatively large screens with portability. Their form factor encourages uses in situations in which the user stands or walks, for example teachers can control simulations in class and nurses can track patients on interactive clipboards [7]. Although commercial tablets offer intuitive interaction techniques such as a *swipe* to displace an object or a *tap* to select an item, they do not fully exploit the range of interaction possibilities found in the research literature. In particular, tablets are not designed to support bimanual input, despite the demonstrated ability to increase performance [18] and precision [4], as well as to enhance the user experience [16, 29].

Existing bimanual interaction techniques were designed for independently supported displays or tabletops. Portable devices pose an additional challenge: how to account for the need to hold the device while interacting with it. Very small devices, such as PDAs and smart phones, offer limited possibilities for bimanual interaction, usually just typing with both thumbs. Multi-touch tablets, with their larger screens, offer as-yet unexplored opportunities for true bimanual interaction. Our goal is to better understand the design space for bimanual, multi-touch interaction on hand-held tablets and to demonstrate how designers can obtain the benefits of bimanual techniques, taking into account the challenge of supporting the device while interacting with it.

We begin by analyzing the related literature and describe a preliminary study that investigates how users hold tablets as they interact. Next, we present the *BiTouch* design space which identifies the key dimensions for designing bimanual multi-touch interaction. We next present BiPad, a toolkit that helps designers add various bimanual interaction to off-the-shelf multi-touch tablets, illustrated with three sample applications. We also report the results of an experiment that compares one- and two-handed interaction performance with respect to tablet orientation, finger placement and interaction technique. We conclude with implications for design and directions for future research.

RELATED RESEARCH

Desktop-based bimanual interaction techniques increase both performance and accuracy [1, 5, 12] and are more convenient when performing highly demanding cognitive tasks [16, 10]. Some techniques provide symmetric control [2]. For example, *Symspline* gives both hands equal roles when manipulating curves [15]. However, most bimanual interaction techniques build upon Guiard's *kinematic chain model* [9], based on his observations about the asymmetric relationship between the two hands [1]. For example, toolglasses, magic lenses and bimanual palettes [5, 3, 17] each use the non-dominant hand to control the position of an interactive palette while the dominant hand selects specific functions.

Bimanual Interaction: Stationary Multi-touch Surfaces

Multi-touch tables and graphics tablets are inherently well-adapted to bimanual interaction, since the user can use multiple fingers from either or both hands. Studies have shown that bimanual interaction techniques can improve performance [6, 14] and selection accuracy [4]. However, these studies assume that both hands are free to interact, e.g. on a stationary multi-touch surface or a small multi-touch device placed on a table. We are interested in hand-held tablets which require at least one hand to support the device, thus restricting the ability to interact.

Bimanual Interaction: Small Portable Devices

Commercially available PDAs and smart phones are designed primarily for one-handed interaction [20] due to their small size. Most interaction is accomplished with the index finger, although some techniques use the thumb, since it can reach the screen from most carrying positions [11, 13, 22]. Other approaches use the outer frame of the phone to improve pointing accuracy [8] or to disambiguate among actions and enrich the interaction vocabulary [21].

Several research prototypes offer the potential for bimanual interaction by adding hardware. For example, *HandSense* [27] uses capacitive sensors to distinguish among six different grasping styles. One could create simple bimanual tasks by allowing these grasps to modify the actions of the dominant interaction hand. An alternative is *HybridTouch* [25], which adds a rear touchpad to a PDA to enable simultaneous front and back interaction.

Wobbrock et al. [28] investigated how different hand positions on the front or back of a handheld device affect interaction performance with the index finger or the thumb. They found that the index finger performed best in all conditions, front or back, and that horizontal movements were faster and more accurate. Although useful for comparing thumb and finger performance on small devices, additional research is needed to understand bimanual interaction on larger portable devices, such as multi-touch tablets.

Bimanual Interaction: Multi-touch Tablets

Hand-held tablets offer new possibilities for bimanual interaction. Although their larger screen size and bezels make two-handed thumb typing less convenient, they also afford various support positions and can accommodate interaction with the thumbs and multiple fingers from both hands.

To date, most bimanual interaction techniques require additional hardware, e.g. to detect touches on the back or sides of the device. For example, *RearType* [24] includes a physical keyboard on the back of a tablet PC. Users hold it with both hands while entering text, thus avoiding an on-screen keyboard and graphical occlusion by the fingers. *Lucid Touch* [26] is a proof-of-concept see-through tablet that supports simultaneous touch input on the front and on the back of the device. Users hold the device with both hands, with thumbs on the front and remaining fingers on the back. The device is small enough that users can reach the entire screen, allowing multi-touch interaction with both support hands without graphical occlusion. However, the arm-mounted camera currently makes this approach impractical.

Another intriguing possibility is *Gummi* [23], a prototype "bendable" tablet that enables limited bimanual interaction by deforming the device. For example, a user could scroll through a list via a 2D position sensor on the back and then select an item by bending the device. Such dual-surface approaches are well suited for simple selection and navigation tasks [30], but are less appropriate for complex tasks that require additional input from the back or when users adjust how they hold the tablet.

Our goal is to incorporate bimanual interaction on tablets, using only the multi-touch surface without additional hardware. The next section describes a preliminary study that investigates how users unconsciously hold tablets while interacting with them, as they sit, stand and walk.

PRELIMINARY STUDY: HOLDING TABLETS

Studying how people 'naturally' hold tablets is tricky. Rather than asking directly, we asked users to perform a distractor task while observing how they held the tablet.

Participants. Six men and two women, average age 30. Four owned iPads, four had never used a tablet.

Apparatus. Apple iPad1 (display: 9.7", weight: 680 g, dimensions: $19 \times 24.3 \times 1.3$ cm).

Procedure. We told participants that we were interested in how pointing and scrolling performance varies as people sit, stand and walk, given different tablet orientations. This was intentionally misleading, since we were really studying how they unconsciously held the tablet while interacting with it. The true experiment was a [2x3] within-subjects design with two factors: tablet *orientation* (landscape, portrait) and *stance* (sit, stand, walk), with tablet *hold* as the dependent measure. The distractor tasks were *pointing* (tapping five successive on-screen targets) and *scrolling* (moving a slider's thumbwheel from one end to the other). Pointing targets were distributed across six equal squares on the screen; slider

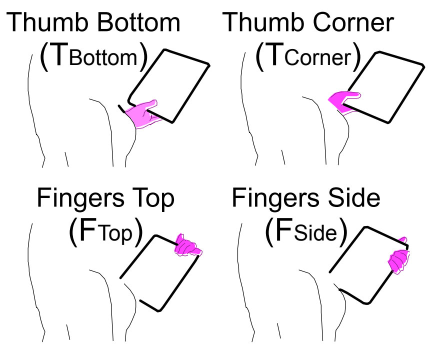

Figure 2. Five spontaneous holds (portrait orientation).

positions included the four screen borders and horizontally and vertically in the screen center.

Participants were asked to hold the iPad comfortably and perform each task as quickly as possible. They were allowed to adopt a new hold only when beginning a new block. Sessions lasted approximately 45 minutes. At the end, we debriefed each participant as to the true goal of the study to learn how they chose to hold the tablets. We first asked them to reproduce the holds they had used and then to adapt them so that the fingers or thumb of the support hand could reach the touch screen. We asked them to rate comfort and ease of interaction when using the support hand to interact and whether they had suggestions for other holding positions.

Data collection. We videotaped each trial and coded how participants supported the tablet with the non-dominant hand, wrist or forearm. We collected touch events, including those that occurred outside experiment trials and while reading instructions. We also measured completion time per trial.

Results

We did not find a single, optimal hold and found significant differences according to experience. All four novices used the same uncomfortable position: the fingers, thumb and palm of their non-dominant hand supported the center of the tablet, like a waiter holding a tray. Novices found this tiring but worried that the tablet would slip if they held it by the border. None found other holds. In contrast, the four experts easily found a variety of secure, comfortable holds. We identified ten unique holds, five per orientation, all of which involved grasping the border of the tablet with the thumb and fingers. Fig. 2 shows these five holds in portrait mode, with the thumb on the bottom, corner or side, or the fingers on the top or side.

Table 1 shows how these holds were distributed across the six conditions: most common was F-side (41%), least common was T-side (9%). The latter was deemed least comfortable, especially in landscape mode, but participants felt that they could use it for a short time. Experts tried nine of ten possible holds in the sitting and walking conditions, but only six when standing, omitting F-top or T-side in both orientations. Individuals varied as to how many unique holds they tried, from three to eight of ten possible. All switched holds at least

Table 1. Total holds per condition (expert users)

	F_{side}	T_{bottom}	F_{top}	T_{corner}	T_{side}
Landscape	3	4	4	4	1
	8	4	0	4	0
	4	4	7	0	1
Portrait	8	3	1	0	4
	8	4	0	4	0
	8	1	3	1	3
	41%	21%	16%	14%	9%

once and two switched positions often (50% and 66%) across different blocks of the same condition.

We were also interested in whether *accidental touches*, defined as touches located more than 80 pixels from the target or slider, during or outside of experiment trials, interfered with intentional touches by the dominant hand. Experts who carried the tablet by the border made very few accidental touches (3%). All were with the dominant hand, far from the screen border, suggesting that they unconsciously prevented the support hand from touching the screen.

Design Implications

First, tablets can feel heavy and users are more comfortable when they can change orientation or swap the thumb and fingers. We should thus seek a small set of roughly equivalent bimanual interactive holds that are easy to shift between, rather than designing a single, 'optimal' hold. Second, users can use the thumb and fingers of the support hand for interaction. We can thus create interactive zones on the edges of the tablet, corresponding to the holds in Fig. 2, which were not vulnerable to accidental touches. Fig. 3 shows these zones in portrait and landscape mode. Although changes in the form factor of a tablet, such as its size, shape or weight, may affect these holds, users are still likely to shift between holds for comfort reasons, just as when reading a book or holding a notebook.

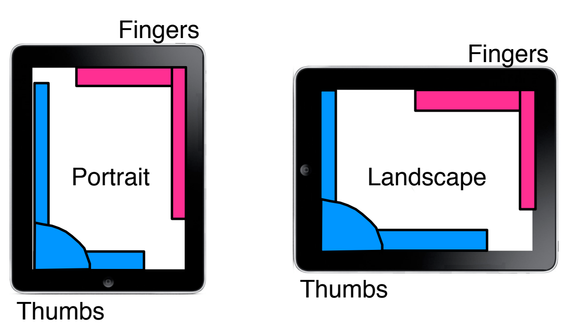

Figure 3. Five support-hand interaction zones.

The next section describes BiTouch, a design space for exploring how to incorporate bimanual interaction on hand-held multitouch tablets.

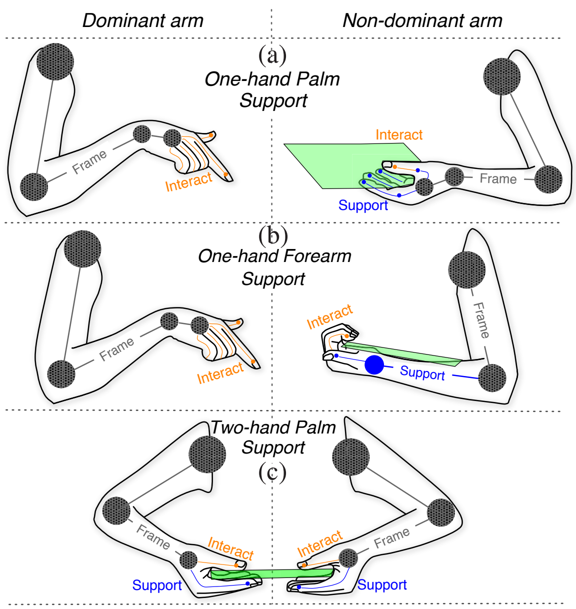

Figure 4. The user creates a spatial *frame*, *supports* the device, and *interacts* with it. Different holds offer different trade-offs with respect to interactive power and comfort.

BiTouch DESIGN SPACE

Unlike desktop PCs or multi-touch tables, bimanual interaction on hand-held tablets must account for the dual role of the non-dominant hand as it simultaneously carries the tablet and interacts with it. Although we designed the BiTouch design space to explore bimanual interaction on hand-held tablets, the reasoning applies to a wider range of human-body interaction with objects [19] and devices ranging from small, mobile devices to large, fixed interactive tables or walls.

Kinematic Chain: Frame, Support, Interact

The first step is to understand the complementary roles of support and interaction. Guiard's [9] analysis of bimanual interaction emphasizes the asymmetric relationship commonly observed between the two hands. He proposes the kinematic chain as a general model, in which the shoulder, elbow, wrist and fingers work together as a series of abstract motors. Each consists of a proximal element, e.g. the elbow, and a distal element, e.g. the wrist, which together make up a specific link, e.g. the forearm. In this case, the distal wrist must organize its movement relative to the output of the proximal elbow, since the two are physically attached.

Guiard argues that the relationships between the non-dominant and dominant hands are similar to those between proximal and distal elements: the former provides the spatial frame of reference for the detailed action of the latter. In addition, the movements of the proximal element or non-dominant hand are generally less frequent and less precise and usually precede the movements of the higher frequency, more detailed actions of the distal element or dominant hand.

We see the kinematic chain in action when users interact with hand-held tablets: the non-dominant hand usually supports the tablet, leaving the fingers and thumb of the dominant hand free to interact. Fig. 4 shows three bimanual alternatives, based on the location of tablet support within the kinematic chain: the palm or forearm of the non-dominant arm (Fig. 4a, 4b); shared equally between the palms of both hands (Fig. 4c). In each case, the most proximal links control the spatial frame of reference; support links are always intermediate between framing and interaction links; and the most distal links use whatever remains of the thumb and fingers to interact.

Table 2. Trading off *framing*, *support* and *interaction* functions of the kinematic chain with respect to the body and the device.

Framing	
Location:	proximal link in the kinematic chain
Distribution:	1 – n body parts
Support	
Location:	none or middle link in the kinematic chain
Distribution:	0 – n body parts
Independence:	0% – 100% body support
Interaction	
Location:	distal link in the kinematic chain
Distribution:	1 – n body parts
Degrees of freedom:	0% – 100% body movement
Technique:	touch, deformation,...

The preliminary study highlighted ten user-generated support holds that permit the thumb or fingers to reach the interactive area. Each poses trade-offs between comfort and degrees of freedom available for interaction. For example, supporting the tablet with the forearm (Fig. 4b) provides a secure, stable hold but forces the fingers to curl around the tablet, leaving little room for movement. In contrast, holding the tablet in the palm (Fig. 4a) gives the thumb its full range of movement, but is tiring and less stable.

Note that comfort is subjective, influenced not only by the physical details of the device, such as its weight, thickness and size of the bezels, but also by how the tablet is held. For example, shifting between landscape and portrait orientations changes the relative distance between the tablet's central balance point and the most distal part of the support link. The tablet acts as a lever: users perceive it as heavier as support moves further from the fulcrum. The next step is to formalize these observations into a design space that describes existing and new bimanual holds and interaction techniques.

BiTouch Design Space

Table 2 summarizes the key dimensions of the BiTouch design space, according to framing, support and interaction functions of the kinematic chain. Each is affected by the relationship between specific characteristics of the human body, the physical device and the interaction between them.

Framing is handled at the most proximal *locations* within the kinematic chain and may be *distributed* over multiple parts of the body. ***Support*** always occurs in *locations* within the kinematic chain, distal to the frame. Support may be completely *distributed* over one or more body parts, symmetrically or not; shared with an *independent* support, e.g. a table or lap; or omitted, e.g. interacting on a freestanding interactive table.

Interaction is always handled at the most distal *location* in the kinematic chain, immediately after the support link. Interaction may be *distributed* across one or more body parts, often incorporating the thumbs or sets of fingers. The *degrees of freedom* available for interaction depend upon what remains after framing and support functions have been allocated, e.g. a finger tip, and the inherent movement capabilities of the body part, e.g. the pinky has little independent movement compared to the index finger. Possible *interaction techniques* are affected by all of the above, as well as the technical capabilities of the device. For example, touch sensors might appear on the front, side or back of the device, or the device itself might be deformable.

Hands that interact as well as support the device have fewer degrees of freedom available for movement. We thus expect the support hand to be non-dominant, capable of limited interaction, e.g. mode switches or menu choices, that frame the interaction of the freer dominant hand.

The BiTouch design space allows us to describe all of the user-generated holds from the preliminary study, as well as many from the literature, e.g. bimanual interaction on free-standing interactive tabletops. It also suggests directions for designing new bimanual interaction techniques. For example, although the hold in Fig. 4c did not appear in the preliminary study, it becomes an obvious possibility if we examine ways to share support across hands. Similarly, once we understand which thumbs or fingers are available for interaction and what constrains their potential movement, we can design novel interaction techniques.

The five basic holds in Fig. 2 can each support an interactive area on the edge of the tablet, reachable by either the thumb or fingers of the support hand. The BiTouch design space helps us create a set of novel bimanual interaction techniques that take into account the potential of the thumbs and fingers at the end of the kinematic chain. For example, all thumbs and fingers have at least a small amount of mobility available to perform *Taps*. The thumb in the T_{corner} hold is fully mobile and can perform *Gestures*. The presence of multiple fingers in the F_{side} hold makes it possible to perform *Chords*. The non-dominant role of the support hand suggests that these *Taps*, *Gestures* and *Chords* can be used to frame more elaborate interaction by the dominant hand, e.g. to select a menu item or to shift color while drawing a line.

BiPad TOOLKIT AND APPLICATIONS

Based on our preliminary study and the BiTouch design space, we designed the BiPad toolkit to help developers add bimanual interaction to off-the-shelf multi-touch tablets. BiPad creates five interactive zones, corresponding to those in Fig. 2, where the fingers or the thumb of the supporting hand can interact.

Software Prototype

The BiPad toolkit, written in Objective-C on Apple's iOS operating system, supports the development of bimanual applications as follows:

BiPad applications consist of one or more views, widgets and controllers, similar to standard iOS applications. The framework lays out the interface in the main view to control

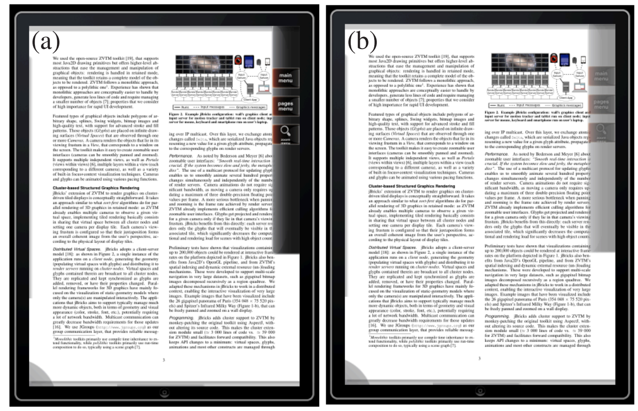

Figure 5. BiPad. a) F_{side} zone is active; other zones are shrunken. b) Unused zones remain partially visible if commands were assigned.

overlay feedback and advanced input management required to enable BiTouch interaction. The application defines BiPad-enabled functions that can be mapped to interactions with the support hand. For example, a text editing application could define `shift` and `num` functions equivalent to pressing the shift or number keys of a virtual keyboard.

BiPad zones appear on the sides and corners of the screen (Fig. 5). Applications can define various interactions for the support hand and modify the default visual representation, e.g., buttons for taps and guides for chords. Zones are displayed as 80-pixel strips, of which the 40 outermost are semi-transparent, on top of the edges of the application view. Zones may be permanently or temporarily visible and the user's hand position determines which is active. Temporarily visible areas shrink automatically when not in use, displaying only a narrow semi-transparent strip of pixels on the appropriate side. Touching once on the outer part of a shrunken BiPad zone causes it to slide out and enables interaction. If a zone contains interaction widgets and is configured to be temporarily visible, it does not shrink completely but remains semi-transparent (Fig. 5b).

BiPad Interaction Techniques

BiPad introduces three predefined interaction techniques for the support hand: bimanual *Taps*, *Chords* and *Gestures*. Bimanual *Taps* involve a press-and-release action on a button within a BiPad zone, using a finger or the thumb (Fig. 6a). Bimanual *Chords* involve multiple fingers pressing down simultaneously within a BiPad zone, and are not possible with thumbs. Fig. 6b shows how pressing the 'stroke' button with the index finger adds additional finger positions below. The user can adjust the stroke size by holding down a second finger on the appropriate button.

Bimanual *Gestures* involve sliding the thumb or finger, starting from a BiPad zone or from an edge related to a BiPad zone, as in Bezel Swipe [21]. In the border zones, *Gestures* are limited to orthogonal movements from the edge, but offer additional degrees of freedom for the thumb in the corner (up-to-down, right-to-left and diagonal). Small stroke shapes indicate the direction of the gesture and its function (Fig. 6c).

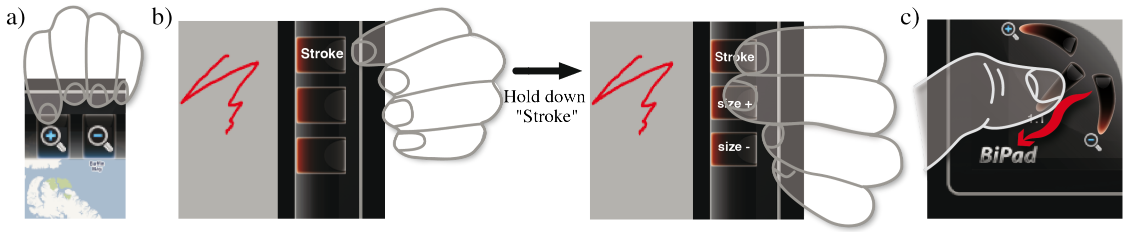

Figure 6. BiPad interaction techniques: a) Taps on buttons. b) Chords with multiple fingers. c) Gestures in multiple directions.

The application defines which BiPad interaction(s) will trigger which function in which zone(s). Applications can specify several interaction techniques for the same function depending upon which BiPad zone (and therefore *Hold*) the user registers. For example, an application might specify that a *Tap* with a finger on the F_{side} zone and a downward *Gesture* with the thumb in the T_{corner} zone will both shift modes for the dominant hand, triggering a pop-up menu rather than selecting an on-screen object.

BiPad Applications

We used BiPad to implement three applications that illustrate how to add bimanual interaction to handheld tablets (Fig. 1).

Quasi-modes and Shortcuts

BiPDF (Fig. 1a) is a PDF reader that uses standard touch gestures to navigate through pages, scroll or zoom the document. A pie menu contains additional commands, e.g. first/last page. As with many tablet applications, the user must touch and dwell to activate the menu instead of executing a gesture. We added a bimanual tap that speeds up interaction: while the user is touching the screen with the dominant hand, a tap on a BiPad button activates the menu immediately.

BiText (Fig. 1b) lets users create custom bimanual shortcuts for text entry, e.g. a button for the '`space`' key and a quasi-mode button for the soft keyboard's '`keypad`' key. Although the dominant hand can also reach these keys, it requires extra movement. The user can also assign any key from the keyboard to a BiPad button by simultaneously pressing the two. Modifier keys, such as the '`keypad`' key become quasi-modes: they activate the mode as long as they are being pressed. Two other BiPad buttons accept or reject the suggestions from the standard text completion engine, reducing movements by the dominant hand.

Menu navigation

BiSketch uses BiPad *Chords* to navigate a tool menu. First-level items, e.g. `color` or `stroke`, appear in the BiPad zone. The user chooses a tool and holds down the corresponding finger in the BiPad zone to trigger the next menu level. The user can then use another finger to select the desired option, e.g., `color` then `red`. Chords can trigger frequently used tools or options while drawing with the dominant hand.

Spatial multiplexing

The previous example refers to two-handed interactions based on temporal multiplexing. BiPad can also handle spatially multiplexed tasks. BiMap (Fig. 1c) lets users zoom in and out by pressing buttons with the support hand. They can select part of the map larger than the view port by (i) selecting with the dominant hand; (ii) simultaneously controlling the zoom factor with the non-dominant hand; and (iii) continuing to change the selection with the dominant hand.

EXPERIMENT

We ran a controlled experiment to determine whether BiPad bimanual interaction techniques outperform a common one-handed technique. We also wanted to see if the BiTouch kinematic chain analysis successfully identifies which bimanual holds are most comfortable and efficient.

We asked participants to stand while holding a multi-touch tablet, using one of the holds identified in the preliminary study. We then asked them to perform a series of bimanual *Taps*, *Gestures* or *Chords*, using the thumb or fingers of the non-dominant support hand to modify the actions of the dominant hand. The key research questions were:

Q1 Are two-handed BiPad techniques faster than a similar one-handed technique?

Q2 What are the trade-offs among the different bimanual holds, orientations and interaction techniques?

Participants. Nine men, three women, all right-handed, aged 22-35. Six own a touch-screen phone, one owns a tablet PC.

Apparatus. iPad1 (display: 9.7" , weight: 680g, dimensions: 190 × 243 × 13 mm), running BiPad.

Procedure. We conducted a $[2 \times 5 \times 3]$ within-subjects design with three factors: ORIENTATION (portrait, landscape), HOLD ($F_{side}, F_{top}, T_{bottom}, T_{corner}, T_{side}$), corresponding to the five BiPad interaction zones, and TECHNIQUE (tap, chord, gesture), i.e. 30 unique conditions, plus the no-BiPad control, a standard one-handed task. We discarded eight conditions as impossible or impractical:

Chords can only be performed with the F_{side} and F_{top} HOLD (both *Orientations*) since a single thumb cannot perform multi-finger interactions.

Gestures were omitted from the F_{side} and F_{top} landscape conditions, since the short edge of the tablet cannot be held steadily on the forearm.

Trials were organized into blocks of 6 trials according to TECHNIQUE, ORIENTATION, and HOLD. Participants were asked to stand and support the tablet with a specified hold. In each trial, the participant touched four successive 80-pixel circular targets with the index finger of the dominant hand while holding the tablet with the non-dominant hand. Targets were arranged randomly around the center of the screen. The first target of a series was always green and one randomly chosen target of the following three targets was red. When the red target appeared, the participant was instructed to use the specified technique to turn the target from red back to green before touching it with the dominant hand.

The four techniques for changing red targets to green include the three BiPad techniques: *Tap*, *Chord*, *Gesture*, and the no-BiPad control condition. The three chords use the index finger and one or both of the remaining fingers of the support hand (middle or ring finger). Gestures slide toward the center of the screen, except for T_{corner}, where the thumb slides up-down, down-up or diagonally. In the no-BiPad control condition, the user touches a button at the bottom of the screen with the dominant hand. The task was chosen to support both pointing and bimanual interaction, including mode switches and quasi-modes.

Participants began with the unimanual no-BiPad control condition, followed by the bimanual BiPad conditions (ORIENTATION, HOLD, TECHNIQUE) counter-balanced across subjects using a Latin square. Although this simplifies the experimental design, it does not account for potential order effects between unimanual and bimanual conditions. On the other hand, all of today's tablets are one-handed and it is unlikely that performing a bimanual task prior to a unimanual one would improve performance on the latter. Indeed, the more likely effect would be a drop in performance due to fatigue. To ensure that participants were familiar with the basic task and both conditions, we asked them to perform a three-trial practice block in portrait mode prior to each no-BiPad condition and to each TECHNIQUE×HOLD condition. They were also allowed to perform a one-trial recall prior to each TECHNIQUE×ORIENTATIONS×HOLD so they the could find a comfortable position for the assigned hold.

To begin an experimental BiPad block, participants touched the specified BiPad zone to register the support hand. Participants were asked to maintain this hold throughout the block and perform each task as quickly as possible. At the end of each condition, they evaluated how comfortable it was to interact with the support hand using that hold. Each session lasted approximately 45 minutes.

In summary, we presented two orientations for no-BiPad, all 10 holds for bimanual taps, eight for bimanual gestures (no landscape thumb holds) and four for bimanual chords (fingers only). We thus collected 216 trials per participant:

- 6 replications of the *no-BiPad* control condition in both ORIENTATIONS (landscape, portrait): 12 trials;
- 6 replications of the *Tap* technique in all HOLD and ORIENTATION conditions: 60 trials;
- 6 replications of the three *Chord* techniques in both ORIENTATIONS for finger-based HOLDS (F_{side}, F_{top}): 72 trials;
- 6 replications of each of the three *Gesture* techniques:
  - two-finger-based HOLDS (F_{side}, F_{top}) in portrait ORIENTATION: 12 trials;
  - two thumb-based HOLDS (T_{bottom}, T_{side}) in both ORIENTATIONS: 24 trials;
  - one thumb-based HOLD (T_{corner}) in both ORIENTATIONS: 36 trials.

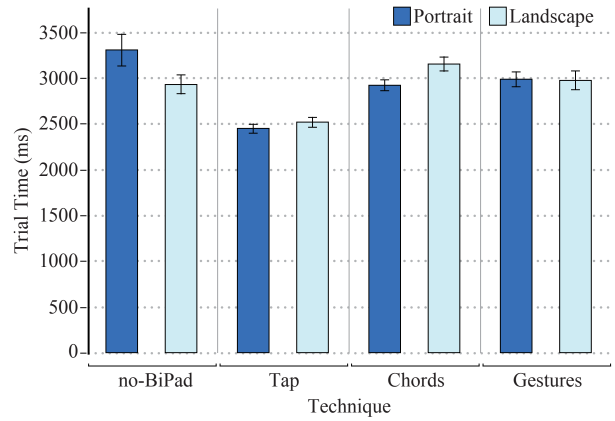

Figure 7. Mean *Trial Time* for each TECHNIQUE by ORIENTATION.

Data Collection. We videotaped each trial and recorded three temporal measures: (i) trial time: from the appearance of the first target to final target selection; (ii) BiPad reaction time: from the appearance of the red target to the first touch in the BiPad area; and (iii) BiPad completion time: from the appearance of the red target to the successful execution of the BiPad interaction. Comfort ratings used a 5-point Likert scale (1 = very uncomfortable; 5 = very comfortable).

RESULTS

We conducted a full factorial ANOVA and handled 'participant' as a random variable, using the standard repeated measures REML technique from the JMP statistical package.

Q1: Bimanual BiPad vs. one-handed interaction

We compared the mean trial time of BiPad techniques to the no-BiPad control condition, using the TECHNIQUE×ORIENTATION ×Random(PARTICIPANT) ANOVA model. We found a significant effect for TECHNIQUE ($F_{3,33} = 16.16$, $p < 0.0001$) but no effect for ORIENTATION ($F_{1,11} = 0.30$, $p = 0.60$). However, we did find a significant interaction effect between TECHNIQUE and ORIENTATION ($F_{3,33} = 8.23$, $p = 0.0003$).

This can be explained by the faster performance in landscape mode for the one-handed no-BiPad condition (Fig. 7): participants performed 11.4% faster ($F_{1,11} = 4.6$, $p = 0.04$) because the distance to reach the button is shorter. Thus, while bimanual taps are significantly faster than the control condition for both orientations (25.9% in portrait and 14% in landscape), bimanual gestures and chords are only significantly faster than no-BiPad in portrait mode (10.4% and 11.7% resp.). In landscape mode, the differences between no-BiPad and bimanual gestures and chords are not significant.

Bimanual taps are significantly faster than bimanual gestures and chords in both device orientations (17.3% and 16.1% in portrait, 14.7% and 19.7% in landscape). Participants significantly preferred bimanual taps (3.5) over bimanual chords (3.3) and gestures (2.7) ($F_{2,22} = 17.5$, $p < 0.0001$). Overall, BiPad techniques were more efficient than the one-handed technique we compared them with.

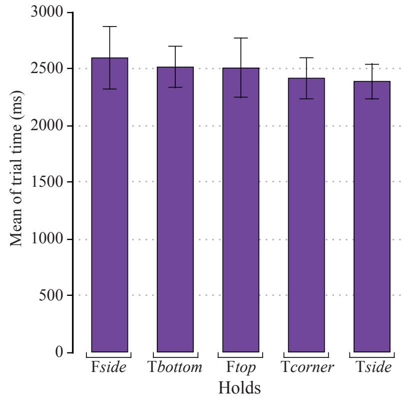

Figure 8. *Tap* performance according to HOLD.

Q2: BiPad tradeoffs: HOLD×ORIENTATION by TECHNIQUE

BiPad Taps

We ran an ANOVA with the model HOLD×ORIENTATION× Random(PARTICIPANT) on trial time for BiPad taps. We found significant effects for HOLD and ORIENTATION ($F_{4,44} = 3.10$, $p = 0.02$ and $F_{1,11} = 5.37$, $p = 0.04$) and no interaction effect ($F_{4,44} = 0.65, p = 0.63$).

For HOLD, Tukey post-hoc tests revealed only one significant result: placing the fingers on the right is slower than placing the thumb on the left side of the tablet for right-handed participants (see Fig. 8). For ORIENTATION, a Student's t-test reveals that portrait is significantly faster (LSM $= 2447.31\,ms$) than landscape (LSM $= 2515.99\,ms$).

Performance among bimanual taps is very similar across conditions, making them suitable for all ten holds. The only significant difference is between fingers and thumbs with a side hold. However, although the F_{side} hold is slightly slower, participants preferred it to the T_{side} hold: fingers are more stable than thumbs and cause less fatigue.

BiPad Gestures

As we discarded the two bimanual holds with fingers placed on the right and top of the device in landscape mode, we examined trial Time for each ORIENTATION condition separately for the remaining eight holds. HOLD has a significant effect on the performance time in both portrait ($F_{4,44} = 4.14, p = 0.01$) and landscape ($F_{2,22} = 4.75, p = 0.02$).

In *Portrait*, post-hoc Tukey HSD tests show that, for a right-handed user, performing gestures with the fingers on the right side of the device is significantly slower than with the thumb on the left side (Fig. 9a). Participants preferred performing gestures with the fingers or with the thumb on the side of the device. In fact, gestures are most difficult to perform when the support hand is placed on the top or bottom of the device when held in portrait mode.

In landscape, where only the *Thumb* placements were tested, performing gestures while supporting the tablet with the thumb on the bottom of the device is significantly faster than in the corner (Fig. 9b). However, since gestures were performed in both ORIENTATION conditions with the thumb, we also compared performance according to thumb holds in both orientation conditions (HOLD×ORIENTATION×Random(PARTICIPANT)).

We found no significant effect of HOLD and ORIENTATION but a significant interaction effect for HOLD×ORIENTATION ($F_{2,22} = 15.08$, $p < 0.0001$). This is because performing gestures with the thumb is significantly faster in portrait, when the support hand is on the side, but significantly slower when the thumb is on the bottom, in which case landscape is faster. The difference between orientations is not significant when the thumb is placed in the corner (Fig. 9c).

The latter effect is interesting and can be explained by the principle of a lever. The greater the distance between the balance point and the most distal support link, the heavier the tablet is perceived. This is considered less comfortable and users find it more difficult to perform gestures. The exception is when the thumb is in the corner: the distal point of the support is equally close to the tablet's balance point in both orientations, thus the two holds are not significantly different. This explanation correlates with the participants' comfort ratings and comments. They preferred to perform gestures with the thumb on the side in portrait and on the bottom in landscape but had no preference for orientation when the thumb is in the corner. Compared to other BiPad techniques, however, gestures were perceived as relatively uncomfortable and practical only for rapid or occasional use.

BiPad Chords

We ran an ANOVA with the model HOLD×ORIENTATION×CHORD TYPE×Random(PARTICIPANT) on *Trial Time*. We found no significant effects of HOLD and ORIENTATION and no interaction effects. For CHORD TYPE, we found a significant effect ($F_{2,22} = 9.09$, $p = 0.01$): holding the index finger down together with the middle finger is significantly faster ($2875\,ms$) than holding down three fingers ($3095\,ms$) or the index and ring finger together ($3131\,ms$).

Participants did not express any significant comfort preferences with respect to chords. However, some participants reported that chords are difficult to perform at the top of the device, especially in landscape mode, due to tension in the arm. Two users could only perform two-finger chords since their third finger could not easily reach the screen.

DISCUSSION

Our results demonstrate not only that hand-held touch tablets can support bimanual interaction, but that it outperforms all tested uni-manual interactions in almost all of our experimental conditions. We created a set of 22 bimanual interaction techniques that combine the ten holds identified in the preliminary study with bimanual taps (10), chords (4) and gestures (8). These offer users trade-offs in performance, comfort and expressive power; BiPad lets users transition smoothly among them.

In the future, we hope to develop the predictive power of the BiTouch design space, building upon our existing understanding of the physical characteristics of the human body and exploring its relationship to hand-held interactive devices. For example, we observed that bimanual taps (in both orientations) and bimanual gestures (in Portrait mode) are significantly faster in holds with thumbs on the side (T_{side}) compared to holds with fingers on the side (F_{side}).

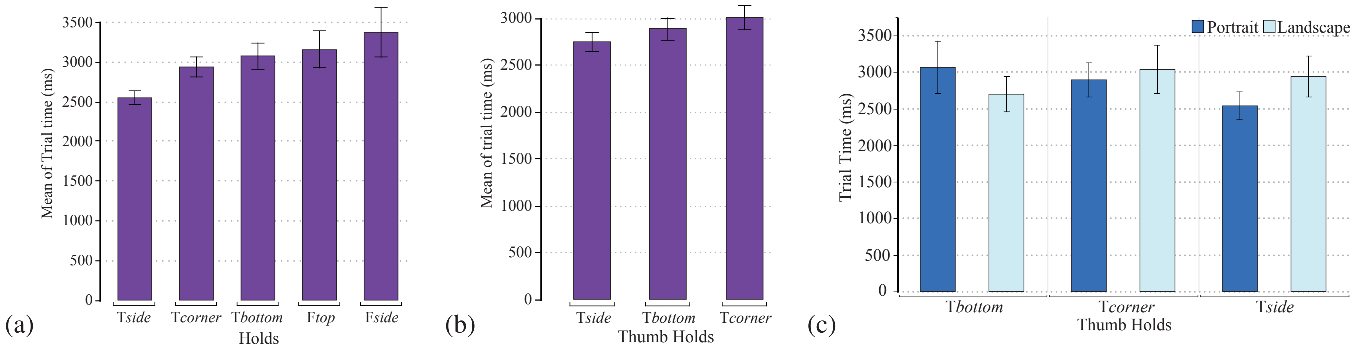

Figure 9. *Gesture* performance according to HOLD (a) in *Portrait*, (b) in landscape, and (c) for the *Thumb* according to HOLD and ORIENTATION.

In contrast, T_{side} is perceived as less comfortable than F_{side}. If we examine thumbs and fingers, we see that the T_{side} hold leaves only two joints available for interaction, whereas the F_{side} hold has three. This suggests that, all other things being equal, performance will be better with interaction techniques that offer a wider range of movement. Additional research is necessary to verify if this prediction obtains for other holds.

We can also use the BiTouch design space to help us understand differences in perceived comfort. One hypothesis is that comfort is correlated with perceived weight, which is determined by both the location of support in the kinematic chain and the orientation of the tablet. If we examine the two holds, we see that the support link for the F_{side} hold, the forearm, is longer than that for the T_{side}, the palm. On the other hand, the former hold restricts movement more than the latter. This suggests two open research questions:

1. Does performance decrease and comfort increase with longer support links?
2. Does performance decrease and comfort increase with increased support link mobility?

We also observed a major effect of tablet orientation in some conditions, such as bimanual gestures. The previously mentioned lever effect plays a role here. If we view the tablet as an extension of the support link, we can estimate its perceived weight based on the distance from the most distal element of the support link to the balance point of the tablet. This raises the question:

3. Do performance and comfort increase as the distance to the balance point decreases?

Finally, multitouch tablets exist in a variety of different shapes, sizes, and weights. We used the popular iPad1 for the first experiment. However, when the iPad2 was released, we replicated the experiment with six participants, and found no significant differences despite the 30% reduction in weight. Of course different tablet designs might affect the performance and comfort of BiPad bimanual interaction. In the future, we plan to extend the BiTouch design space to include device-specific characteristics to increase its predictive power.

SUMMARY AND CONCLUSIONS

We investigated how to introduce effective bimanual interaction into hand-held tablets. We began with a preliminary study that identified support positions while sitting, standing and walking. We found that, although novices found it difficult to come up with effective holds, more experienced users produced ten unique holds that can be adapted to support bimanual interaction. We also found that users do not seek a single, optimal hold, but instead prefer to modify their holds over time, to reduce fatigue and increase comfort. We concluded that the design challenge was not to create a single bimanual technique but rather to create a set of equally comfortable and effective techniques.

We next examined the theoretical basis of the ten observed holds and presented the BiTouch design space, based on Guiard's kinematic chain model. We argue that we can understand bimanual interaction with hand-held devices by examining how three functions – framing, support and interaction – are distributed along the kinematic chain. Our goal is to offer *descriptive*, *predictive* and *generative* power, and BiTouch offers a good start: we can describe all of the unimanual and bimanual interaction techniques observed in the preliminary study; we can make informal predictions about which factors affect performance, comfort and expressive power; and we have generated a set of bimanual interaction techniques that offer different trade-offs with respect to the above:

- *Bimanual Taps*: one finger or thumb taps the screen,
- *Bimanual Chords*: several fingers touch the screen,
- *Bimanual Gestures*: a finger or thumb slides on the screen.

We implemented these techniques in BiPad, a user interface toolkit we made for designing bimanual interaction with off-the-shelf hand-held tablets[1], and developed three working applications in which the non-dominant hand can modify the dominant hand's interaction using taps, chords or gestures.

We tested these interaction techniques in a controlled experiment for each of the five holds and two orientations found in the preliminary study. Bimanual taps are faster than reaching on-screen buttons with the dominant hand only, regardless of tablet orientation or hold. However, they can handle at most three buttons, since the pinky cannot reach the screen and the range of thumb movement is limited. Bimanual chords and gestures offer a richer vocabulary for shortcuts to off-screen functions, but have their own limitations. Chords require multiple fingers and gestures are restricted in landscape to thumb

[1]The BiPad toolkit is freely available at http://insitu.lri.fr/bipad

holds. The BiTouch analysis helps explain why bimanual chords and gestures are faster only in portrait orientation: the position of the support link in the kinematic chain directly affects which fingers or thumbs are available for interaction and the number of available degrees of freedom.

Together, the BiTouch design space and the BiPad toolkit offer developers a richer understanding of bimanual interaction and a practical approach for adding bimanual interaction to hand-held tablets. Future work will explore how we can generate new possibilities for bimanual interaction on a range of devices in different mobile settings.

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